Supernova Remnants: Nature's Turbulence Experiment

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A supernova remnant is the term used for the brilliant display produced when the debris of a supernova explosion strikes its immediate surroundings. These surroundings are determined by the last stages of evolution of the massive star progenitor of the supernova explosion. As such, supernova remnants not only provide a unique window into our understanding of supernovae but also of stellar evolution and turbulent mixing.

Scientists at LANL have formed a multi-institutional team to study the evolution of supernova remnants, focusing on the nucleosynthetic yields and the explosive mixing as these nuclear products interact turbulently with the surrounding stellar winds.

This year, Carola Ellinger, working with LANL scientists Chris Fryer and Gabriel Rockefeller, conducted a detailed study of the mixing in asymmetric supernovae [1]. Figure 1 shows maps of nuclear abundances at the end of the mixing phase caused as the shock moves through the star. This mixing explains many of the observed features in supernovae like SN1987A where both the hydrogen and helium showed evidence of mixing inward and the iron was mixed outward.

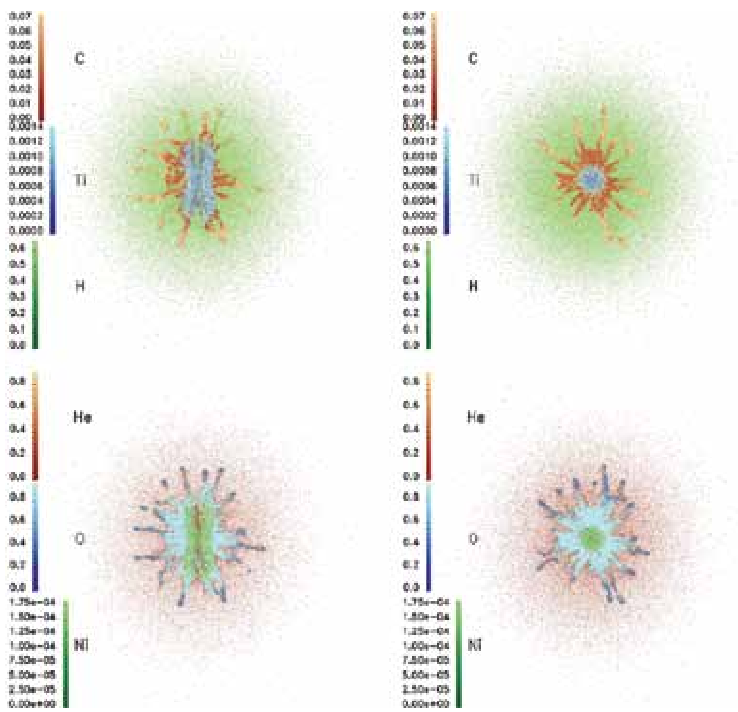

Fig. 1. Abundance maps for a jet-like explosion where the velocity along the axis is four times greater than in the equator. The figure shows slices that are parallel and perpendicular to the polar axis. Hydrogen and helium are visibly mixed inward along the asymmetry axis, while nickel (which will decay to iron) and titanium are mixed somewhat closer into the Rayleigh-Taylor fingers.

One of the most striking supernova remnants is the roughly 330-year-old Cassiopeia A remnant. In 2004, LANL was part of a team that observed Cassiopeia A for a megasecond image on the Chandra satellite [2] (a full 10 days focused on this remnant). These observations provide detailed information of the remnant characteristics, producing spectral data at each pixel of a wide map. Figure 2 shows the image from these observations. First note the detailed turbulent structures produced as the shock plows through the interstellar medium. With the spectral data, scientists are able to determine both the density and temperature of all features in this image. No other experiment, laboratory or astrophysical, can provide such detailed diagnostics of a turbulent event.

The difficulty with using this data lies in understanding (or not understanding) the initial conditions. These initial conditions require both an understanding of the stellar progenitor and the subsequent supernova explosion. LANL was part of the leading effort to model the progenitor of Cassiopeia A [3], placing strong constraints on the mass of the progenitor. From this work, it was realized that the progenitor of Cassiopeia A was definitely a binary system. This makes modeling a bit more difficult, because asymmetries in the remnant profile

(e.g., the apparent "jet" in the Cassiopeia A remnant) could be due to the asymmetries in the circumstellar material, not in asymmetries in the explosion itself.

One way to distinguish circumstellar density asymmetries from explosion asymmetries is to study the asymmetries in material produced in explosive nucleosynthesis, such as ^{56}Ni or ^{44}Ti. NuSTAR (the Nuclear Spectroscope Telescope Array) is the first focusing telescope in the high energy X-ray band (6–79 keV) of the electromagnetic spectrum.

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The decay chain of radioactive ^{44}Ti produces photons in this band, and NuSTAR will be able to map out the ^{44}Ti distribution in supernova remnants. LANL has joined the science team of NuSTAR to produce ^{44}Ti distributions for supernova remnants. Figure 3 shows our first calculation for Cassiopeia A, modeled through the NuSTAR sensitivity band [4]. NuSTAR has now spent over 500 ks observing Cassiopeia A and we expect to finish, within the next six months, a detailed comparison of this NuSTAR data to our simulations.

With the NuSTAR data, we will have firm constraints on the supernova explosion asymmetries. Combined with the data from a host of other satellites, we will finally have constrained initial conditions for Cassiopeia A. With these constraints, we will be able to extract the wealth of physical information from this cosmic physics experiment.

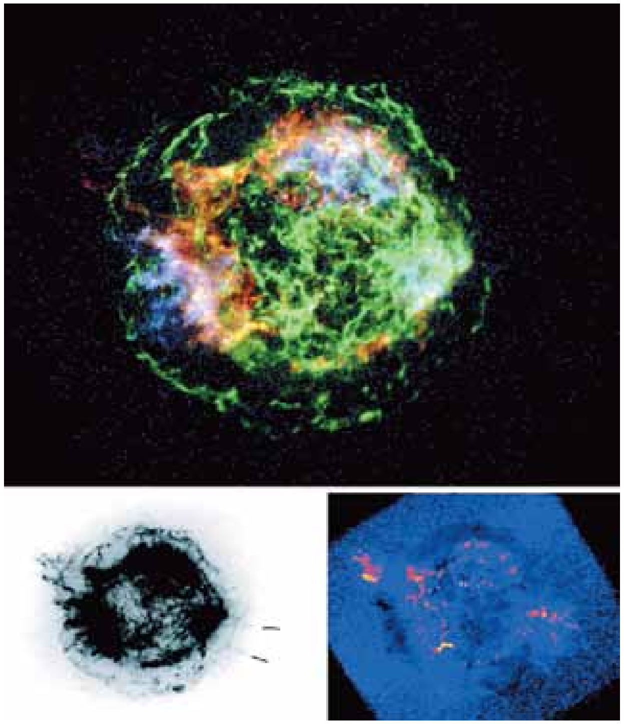

Fig. 2. Three-color image of Cassiopeia A with red corresponding to the Silicon Heα (1.78–2.0 keV) line, blue corresponding to the Fe K (6.52–6.95 keV) line, and green corresponding to the 4.2–6.4 keV continuum. (Bottom left): Overexposed broadband image showing faint features. The spectral regions are indicated (Top left): northeast jet; (Bottom right): on the same scale, the ratio image of the Si Heα (1.78–2.0 keV) and 1.3–1.6 keV (Mg Heα, Fe L), without subtraction of the continuum contribution. The image highlights the jet and counterjet traced by Si emission, although features at the lowest intensity levels are uncertain.

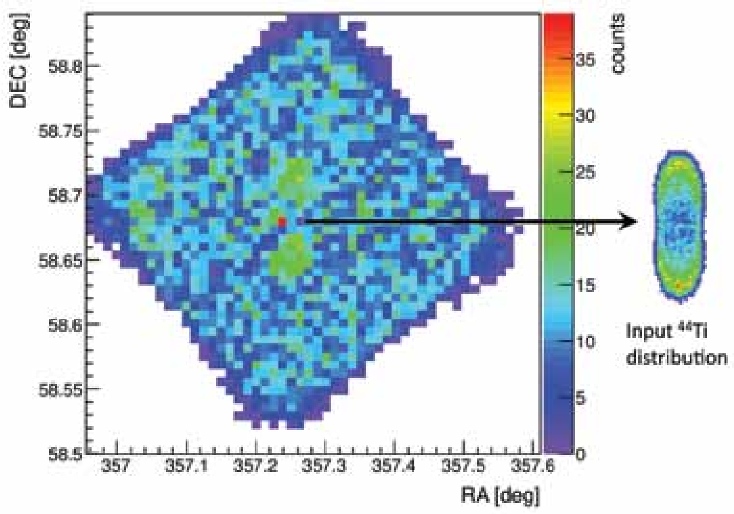

Fig. 3. Color map (denoting intensity) of an asymmetric explosion of Cassiopeia A as viewed by NuSTAR. The asymmetric explosion is a jet-like explosion like that shown in Fig. 1. (The velocity is four times stronger along the axis than the equator.)

[1] Ellinger, C.I. et al., *Astrophys J* **755**, 160 (2012).

[2] Hwang, et al., *Astrophys J* **615**, L117 (2004).

[3] Young, et al., *Astrophys J* **640**, 891 (2006).

[4] Zoglauer et al., American Astronomical Society, HEAD meeting #12, #43.07 (2012).